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# Supercurrent and quasi-particle transport in a two-dimensional electron gas with superconducting electrodes ☆

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**Abstract**

We have investigated supercurrent and quasi-particle transport in the 2DEG present in InAs/Al(Ga)Sb quantum wells. The physics of these systems will be discussed with two examples: (i) supercurrent transport in Nb/InAs/Nb junctions, and (ii) phase-dependent resistance in a superconductor–2DEG quasi-particle interferometer.

*Keywords:* Electrical transport; Indium arsenide; Molecular beam epitaxy; Quantum effects; Quantum wells; Semiconductor–superconductor interfaces; Superconductivity; Superconductivity–semiconductor heterostructures

## 1. Introduction

Recent years have seen a revival of research on transport in hybrid superconducting structures, where superconductors are coupled by either a normal metal or a semiconductor (for a review see Ref. [1]). In particular, the possibility of coupling superconductors to a (ballistic) two-dimensional electron gas (2DEG) has triggered a range of theoretical predictions [2], most of which have not yet or only partially been observed experimentally.

Experiments on quantum ballistic transport in a 2DEG show that the first order description of electron transport is in terms of non-interacting particles or waves [3]. Electron–electron and electron–phonon interactions lead to inelastic scattering, and therefore induce phase breaking. However, at low temperatures the associated length scales for these processes can greatly exceed the sample dimensions.

Similar to the case of normal transport, we therefore assume that the transport through a 2DEG coupled to superconductors can also be described in terms of non-interacting particles. A finite pair potential $\Delta$ is present in the superconducting electrodes, whereas we assume $\Delta = 0$ in the 2DEG itself. With these assumptions the superconductor only affects the transport by means of coherent Andreev reflection. An electron from the 2DEG with energy $E$ (relative to the Fermi energy) $< \Delta$ cannot enter the superconductor and

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will be reflected as a hole, provided that no potential barrier is present at the interface. A crucial aspect here is that, in the absence of a magnetic field and for $E=0$, the wave-functions of the electron and Andreev-reflected hole are phase conjugated. This phase conjugation has led to a range of theoretical predictions [4–7], some of which have been observed experimentally [8–10].

A second aspect is that in the Andreev reflection process, the phase of the particle wave-function changes with $\phi_1$ when the electron is converted into a hole at the first superconductor, and $-\phi_2$ when the hole is converted back into an electron at the second superconductor. As a result, bound electron-hole states are formed in the 2DEG and it can be shown (e.g. for quantum point contacts in Refs. [11,12]) that a supercurrent can flow when the energy of these bound states depends on the superconducting phase difference $\Delta\phi=\phi_2-\phi_1$.

As we will show in Section 4, the superconducting phase difference can not only determine the supercurrent, but can also affect the normal transport properties. In this paper we will illustrate the physics of a superconductor-coupled 2DEG with two examples: (i) supercurrent transport in superconductor/2DEG/superconductor junctions, and (ii) phase-dependent resistance in a superconductor–2DEG quasi-particle interferometer.

## 2. Device description

Our devices were based on the closely lattice-matched InAs/Al(Ga)Sb III/V compound system. A 2DEG was created in an InAs quantum well by confining the electrons between AlSb or GaSb barriers. A special feature of this system is that it is not intrinsically doped. Due to the relatively deep InAs well, and the pinning of the Fermi energy at the surface, the carrier density was about $1.0\text{–}1.5\times10^{16}\ \mathrm{m}^{-2}$. The mobility was typically in the range $50\,000\text{–}100\,000\ \mathrm{cm}^2/\mathrm{V}\cdot\mathrm{s}$, resulting in an elastic mean free path $l_e\approx1\ \mu\mathrm{m}$. An additional feature of the InAs/GaSb system is that due to the special band alignment this system not only contains a 2D electron gas, but may also support a 2D hole gas. However, due to its higher effective mass and lower mobility we expect that the latter contribution to the (super) current can be ignored.

A similar system was employed by Nguyen et al. [13]. Note, however, that in their case the electron density is higher due to intentional doping, and more than one 2D sub-band may be occupied. Due to the relatively low electron density, our systems are strictly two-dimensional.

Superconducting contacts were made by first removing the top GaSb cap and AlSb barrier layers, using a selective wet etchant which exposed the InAs surface. The special property of InAs is that the Fermi energy of the exposed surface is pinned about 150 meV above the conduction band edge. As a result no Schottky barrier is formed when metal is deposited on top. Before the Nb deposition however, the oxide layer on the InAs surface was removed by Kaufmann Ar etching. This is required since the probability of Andreev reflection is severely degraded by the presence of a tunnel barrier at the superconductor–semiconductor interface [14].

## 3. Supercurrent transport in Nb/InAs/Nb systems

Supercurrent transport through a 2DEG has been studied by several groups [13,15–18]. In these cases the 2DEG is formed either due to surface inversion on a $p$-type InAs substrate, or is present in an In(Ga)As quantum well. No conclusive evidence has yet been obtained for supercurrent transport in GaAs/AlGaAs heterojunctions [19–22]. A cross-section of the devices we employ for supercurrent transport is given in Fig. 1. The two superconducting electrodes are 0.25 $\mu$m apart. Due to the fabrication process, the top barrier layer is also removed. Measurements show that this leads to a reduction of the elastic mean free

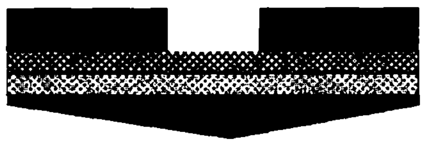


Fig. 1. Cross-section of the devices, illustrating the Nb electrodes connected to the InAs/GaSb quantum well (thicknesses in nm).

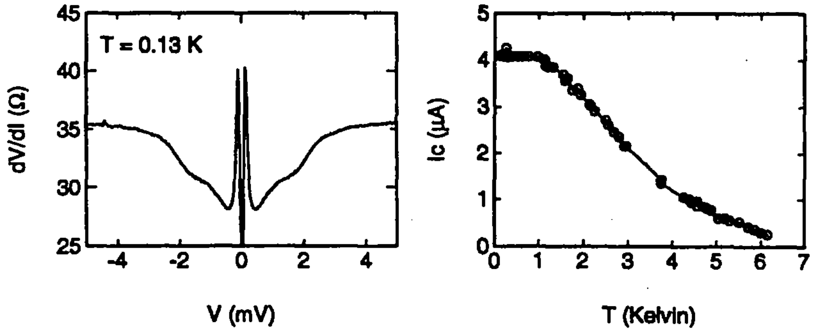


Fig. 2. (a) Differential resistance for a 0.25 μm gap device, measured at 130 mK. (b) Temperature dependence of the critical current of a 0.25 μm gap device.

path to a value $l_e \approx 0.25\ \mu m$. Fig. 2a shows the differential resistance of the sample, measured as a function of voltage bias [24]. For $V \gg 2\Delta$, with the superconducting energy gap of Nb given by $\Delta \approx 1.5$ meV, the normal state resistance $R_n$ is measured. After correction for parallel conductance (due to the absence of a mesa etch), we find that the resistance is about 1.5 times the Sharvin resistance of the 2DEG [3], thus indicating some residual scattering. The decrease in resistance below $V = 3$ mV clearly illustrates the onset of Andreev reflection. The structure at $V \approx 1.5$ mV can be related to multiple Andreev reflection [23].

Relevant for the magnitude of the supercurrent is that the electrode spacing is shorter than the superconducting coherence length $\xi_0 = \hbar v_F/\Delta$ (evaluated for the ballistic case). This implies that the junction is in the short-limit case [25]. Also, at $T = 130$ mK the thermal coherence length $\xi_n = \hbar v_F/kT$ exceeds the junction length. This implies that the $I_c R_n$ product should be given by $\pi\Delta/e \approx 3$ mV [25].

The temperature dependence of the supercurrent is given in Fig. 2b. The zero-temperature critical current is much less than expected from theory. The temperature dependence is also different from that expected for a short and clean junction [25]. Part of the results may be due to the fact that the 2DEG is not fully ballistic. Another aspect is that, since the contacts are fabricated on top of the InAs, the electrons can penetrate a finite distance underneath the superconductor before being Andreev reflected. The transport in such a superconducting quantum well (SQW) was studied theoretically by Volkov et al. [27]. However, we think that the (lack of) ballistic transport underneath the contacts plays an even more important role in degrading the supercurrent. This is supported by recent investigations on the effect of Kaufmann Ar cleaning on the electron density and mobility of the 2DEG [26].

## 4. Phase-dependent resistance in a superconductor–two-dimensional electron gas quasi-particle interferometer

As discussed in Section 1, phase-coherent Andreev reflection can reveal itself as a phase-dependent normal resistance. An example is the phase-dependent resistance in a superconductor–2DEG quasi-particle interferometer [28]. Several schemes for these so-called quasi-particle interferometers have been proposed [5,29–38]. Normal metal–superconductor interferometers have been studied experimentally, using either tunnel junctions [39], or clean contacts [40,41].

We have fabricated and studied an interferometer in the quasi-ballistic regime, with high transparency interfaces between the superconductor and the 2DEG. The geometry is shown in Fig. 3a. A ring-shaped electrode (El.1) is defined on top of an InAs layer. Near the 0.25 μm gap in this electrode a second electrode (El.2) is located, at a distance of 0.3, 1.0, or 2.0 μm. In the experiment the (differential) resistance between electrodes 1 and 2 is measured as a function of the magnetic flux $\Phi$ through the ring.

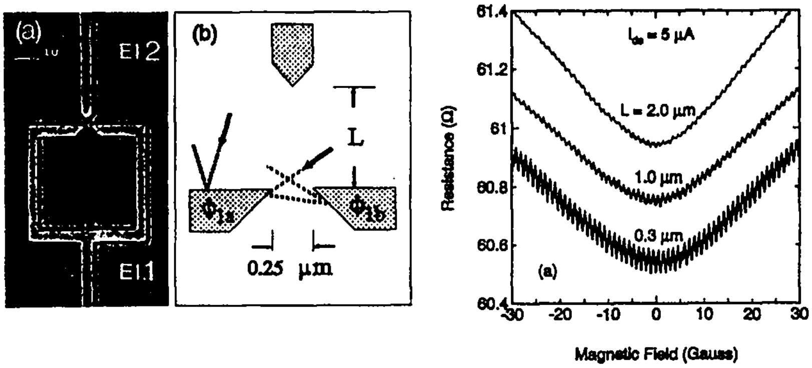


Fig. 3. SEM micrograph (a) and schematic view (b) of the electrodes of the superconductor–2DEG quasi-particle interferometer. (c) Phase-dependent resistance of the device at three different spacings between injector and ring electrode, obtained at 5 $\mu$A DC bias.

Electrode 1 injects electrons into the 2DEG. A fraction of these electrons will end up in the narrow gap in electrode 2, and will sense the phase difference $\Delta\phi = 2\pi\Phi/\Phi_0$, with $\Phi_0 = h/2e$ the superconducting flux quantum. Due to the all-niobium nature of the electrodes, the first-order description is in terms of a SQUID, due to the Josephson coupling between electrodes 2 and 1a, and 2 and 1b, respectively. This behaviour is observed in the measurements of the differential resistance at zero current bias $I_{DC}$. For $L = 0.3$ $\mu$m, the resistance is modulated with a period $h/2e$, and reaches the zero-voltage state whenever the critical current ($I_c \approx 500$ nA) has a maximum at $\Phi = n\Phi_0$. When $L$ is increased, the Josephson coupling becomes weaker ($I_c \approx 40$ nA at $L = 1.0$ $\mu$m) until it can no longer be detected at $L = 2.0$ $\mu$m.

An alternative way to reduce the effect of the Josephson coupling is to apply a DC current bias $I_{DC}$. Fig. 3c shows the measurement of the differential resistance at $I_{DC} = 5$ $\mu$A, a value much higher than the estimated critical currents. Well-defined oscillations are visible, which are attributed to quasi-particle interference. They distinguish themselves from the SQUID-type oscillation by their different period, temperature dependence and dependence on injector spacing $L$ [28]. The oscillations show a resistance minimum at $\Delta\phi = 0$; however, at low voltages and energies a resistance maximum is observed [28]. This behaviour is not yet understood. Recently we have observed similar oscillations in a T-shaped interferometer [42]. Due to the lack of parallel conducting paths in the latter system, the amplitude of the oscillations is typically 1% of the total resistance, which should be compared to the 0.05% modulation in the system described above.

## 5. Summary

We have given two examples of (phase coherent) Andreev reflection in superconductor-coupled 2DEG systems. These show that the fundamental effects predicted by theory are indeed observed in the experimental systems. However, their manifestation is different, either quantitatively or qualitatively. We believe that by improving the device geometry, in particular the 2DEG region near or underneath the superconducting contacts, the comparison with theory can be tightened. Work in this direction is in progress.

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